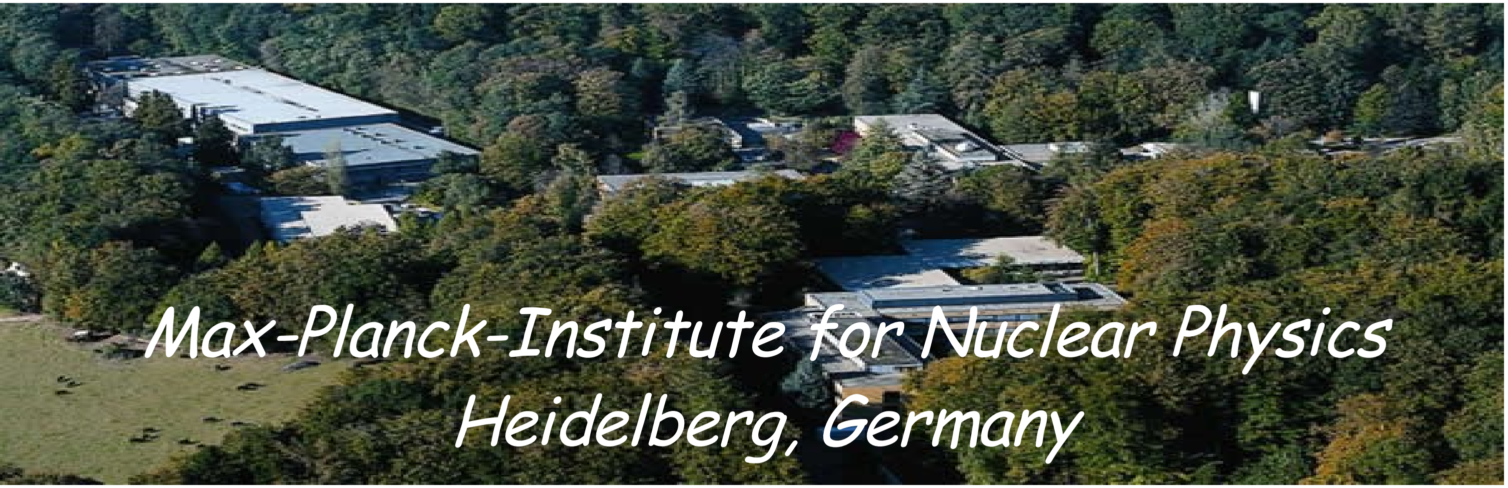
Lepton pair creation in strong laser fields

K. Z. Hatsagortsyan, C. Müller, M. Ruf, G. Mocken, and C. H. Keitel

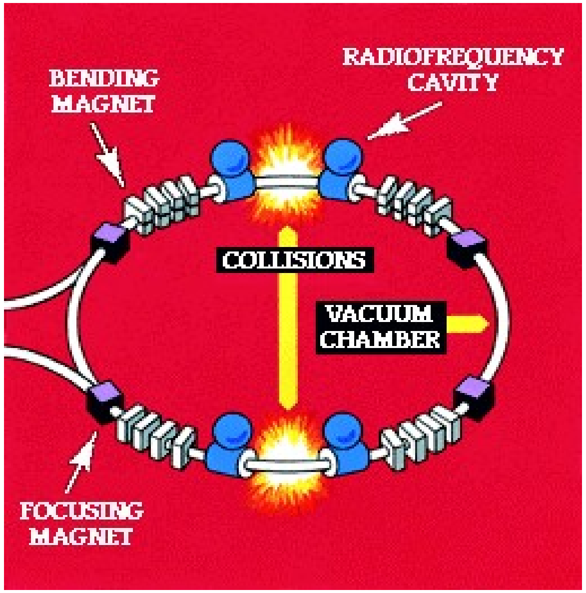


Content

- <u>Laser-driven collider</u>
  - Ps atoms/ Coherent recollisions/high luminosity
  - Muon pair production
- <u>Pair creation in intense laser fields</u>
  - Pair creation in a laser and Coulomb fields:
    free pair creation: prospects for experimental realization
    pair creation with capture of the electron: the role of bound atomic states
  - Pair creation in a standing electromagnetic wave:
    the role of the laser magnetic field

Laser-driven collider

Conventional collider



ε~100 -1000 GeV

$L \sim 10^{32} - 10^{34}$ cm^{-2} s^{-1}

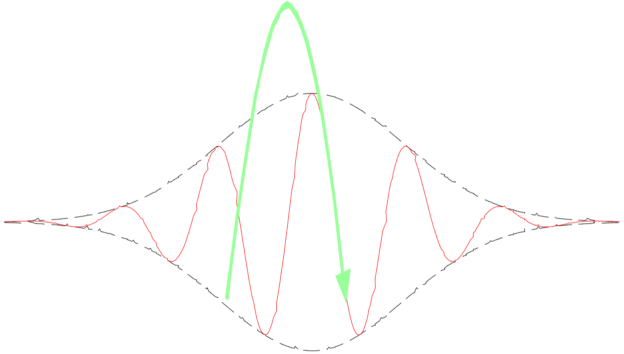
r =1 fm=10^{-13} cm

ε~ ch/r ~1 GeV

$L \sim 10^{26}$-10^{27} cm^{-2} s^{-1}

Laser wakefield accelerators ? $L \sim 10^{21}$ cm^{-2} s^{-1}

Combine acceleration, focusing and collision in a single stage in a laser field



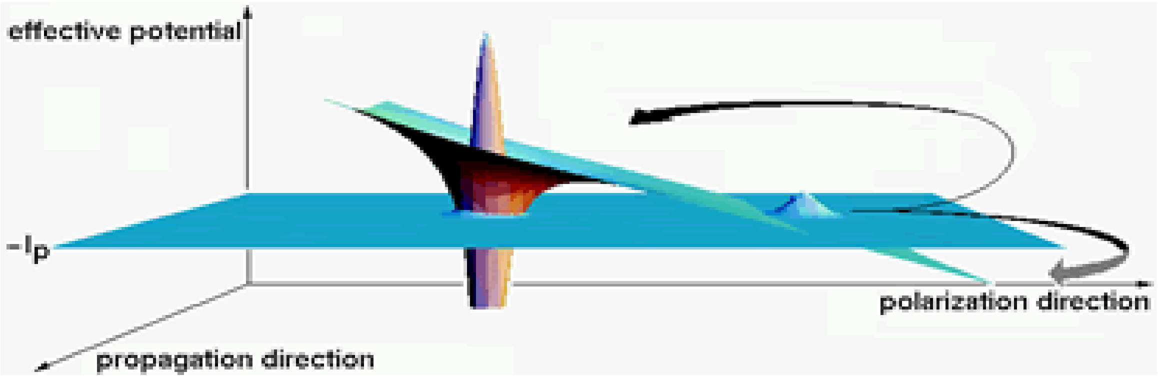
K. Hatsagortsyan et al. EPL **76**, 29 (2006)

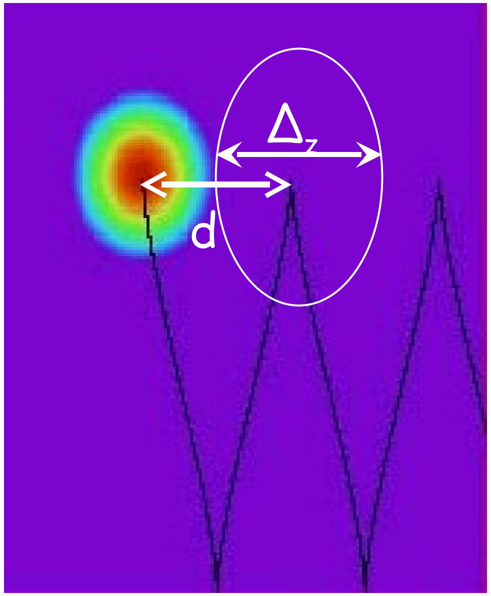
Laser-driven recollisions

Nonrelativistic attophysics:

3-step model

ATI/HHG





Ponderomotive energy $U_p = mc^2 \xi^2 / 4$

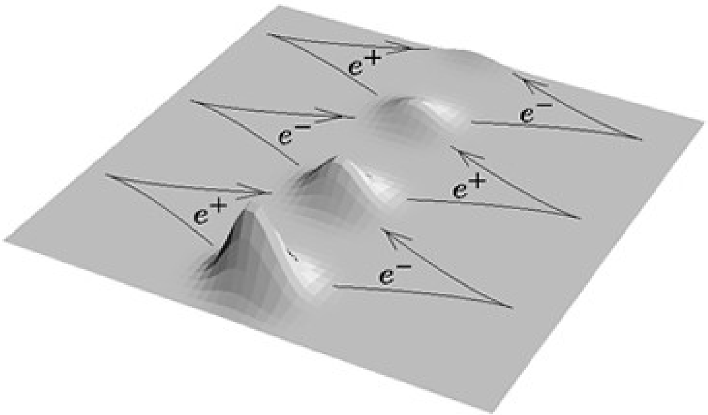
Relativistic regime: $\xi = eE / mc\omega$

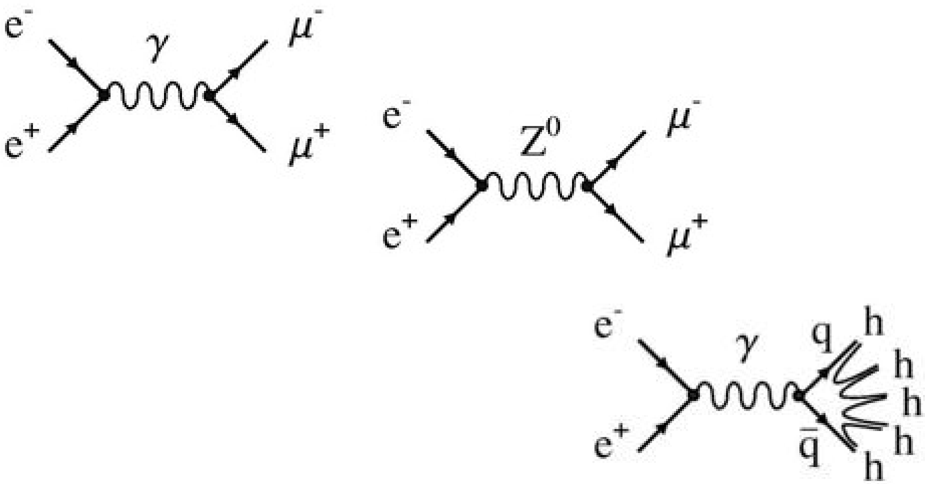
Recollison is suppressed by relativistic drift

$d \approx \lambda \xi^2$

$\Delta_z \approx \Delta v_z / \omega$

Positronium in a laser field





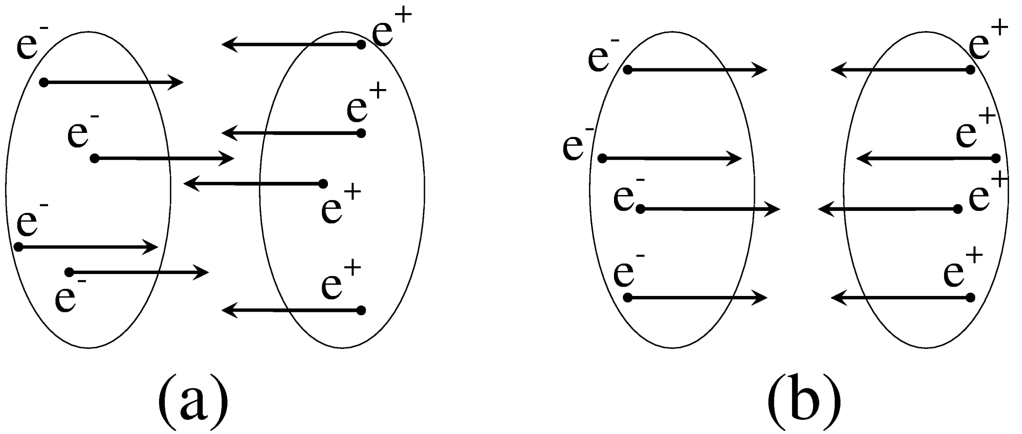
Identical charge-to-mass ratio:

$$F = \frac{e}{c}\left(\vec{v} \times \vec{B}\right) \quad \vec{v} \propto e\,\vec{E}$$

Identical relativistic drift
Periodic electron-positron recollisions

B. Henrich et al. PRL **93**, 013601 (2004)

Coherent recollisions



incoherent coherent

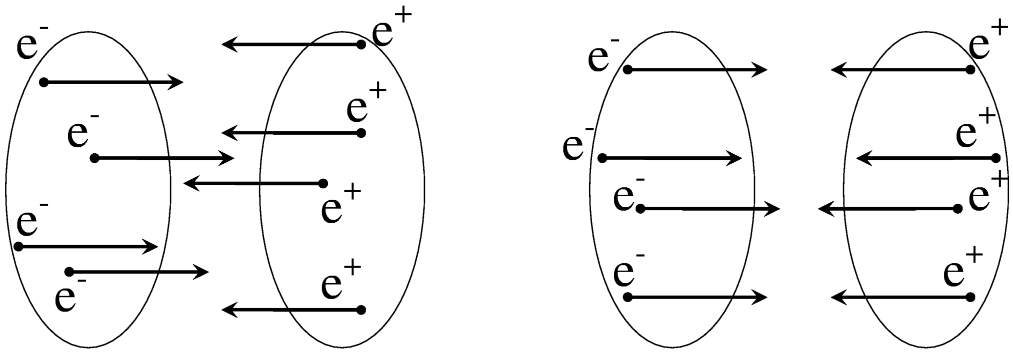
Conventional colliders:

mean impact parameter ~ beam size a_b

Laser-driven Ps:

mean impact parameter ~ electron wave packet size a_w

Coherent recollisions



(a) incoherent (b) coherent

$$\frac{dN}{dt} = \sigma\, L$$

$$L = \left[\frac{N_e (N_e - 1)}{a_b^2} + \frac{N_e}{a_w^2} \right] f$$

Luminosity enhancement due to coherent component

Conventional colliders:

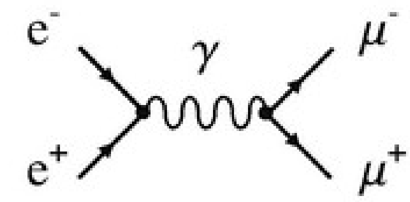
mean impact parameter ~ beam size a_b

Laser-driven Ps:

mean impact parameter ~ electron wave packet size a_w

Laser driven muon production

Ps -> $e^+ e^- \to \mu^+ \mu^-$



Threshold: $2\, mc^2 \xi \geq 2\, Mc^2$ I>4x10[22] W/cm[2]

$$S_{fi} = -i\alpha \int d^4x\, d^4y\, \overline{\Psi}_{p+}(x)\gamma^\mu \Psi_{p-}(x) D_{\mu\nu} \overline{\Psi}_{p-}(y)\gamma^\nu \Psi_{p-}(y)$$

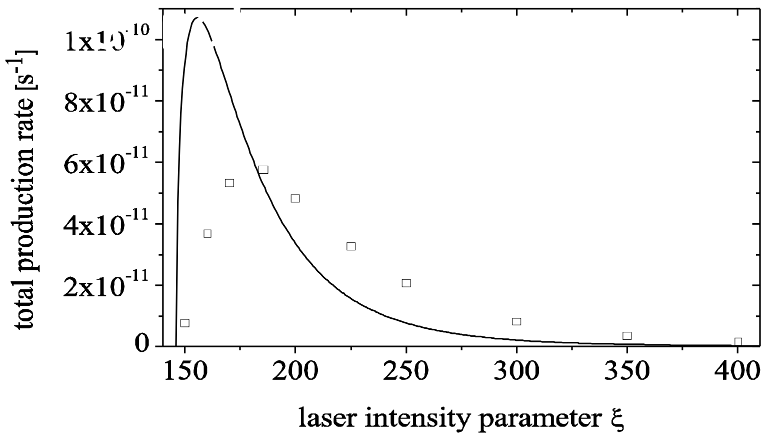
$$S_{Ps\to\mu^+\mu^-} = \int \frac{d^3p}{(2\pi)^3}\, \Phi(p)\, S_{fi}$$

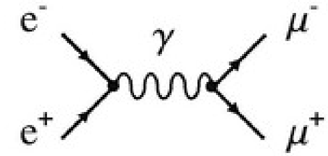
Volkov wave functions

Momentum distribution in Ps ground state

C. Müller et al. PRD **74**, 074017 (2006); PRA **78**, 033408 (2008); PLB **659**, 209 (2008)

Laser driven muon production





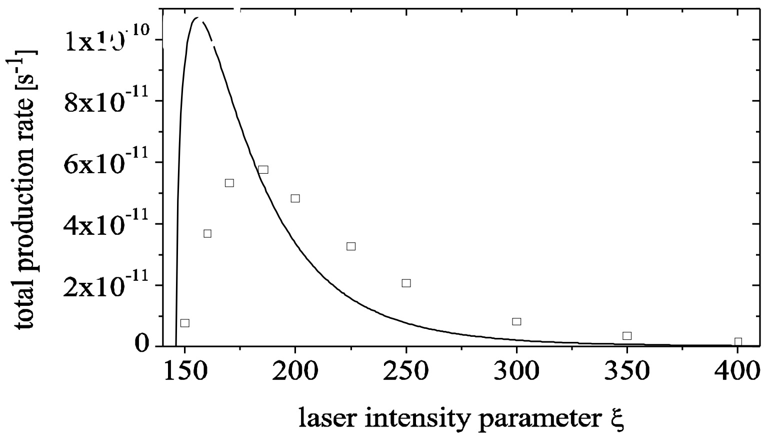
Rigorous QED result can be estimated by simpleman model via field free cross-section σ and electron wave packet spreading:

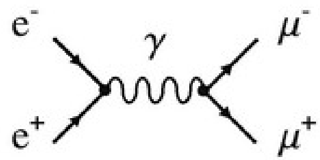
$$R \sim \frac{\sigma}{\xi \left(\alpha \xi \lambda \right)^3}$$

Field-free cross-section

$$\sigma \approx \frac{4\pi}{3} \frac{r_0^2}{\gamma^2} \quad \gamma \sim \xi$$

Laser driven muon production





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$$R \sim \frac{\sigma}{\xi\left(\alpha\xi\lambda\right)^3}$$

$$\delta x' \sim \delta y' \sim \delta z' \sim \frac{\delta p'}{m} t_r' \sim \alpha \xi \lambda$$

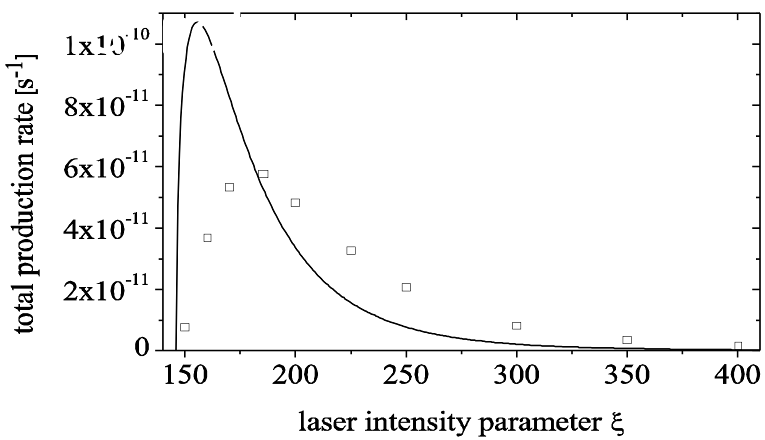
$$t_r' \sim 2\pi\gamma/\omega; \quad \gamma \sim \xi; \quad \delta p' \sim 1/a_0$$

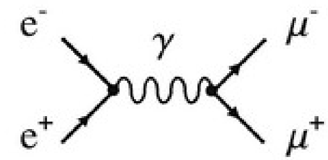
$$\alpha \xi \lambda \sim 10^{-4}$$

Field-free cross-section

$$\sigma \approx \frac{4\pi}{3}\frac{r_0^2}{\gamma^2} \quad \gamma \sim \xi$$

Laser driven muon production





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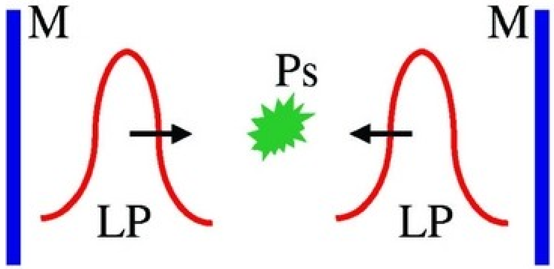
$$t_r' \sim 2\pi \ldots$$

cross-section

$$\ldots \frac{4\pi}{3}\frac{r_0^2}{\gamma^2} \quad \gamma \sim \xi$$

To increase the reaction rate in LDC, the recollision time should be reduced.

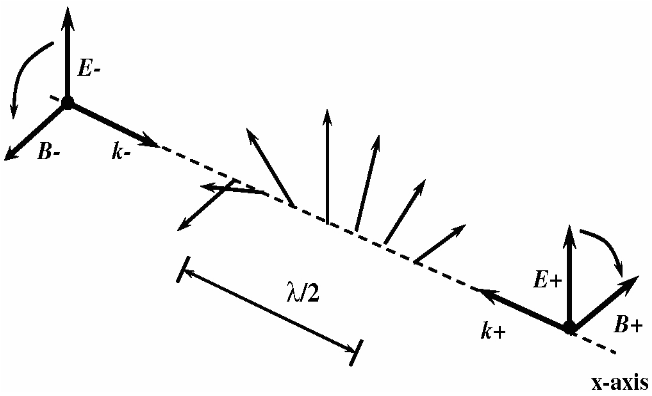
Counter-propagating laser pulses



Short recolision time ~ T/2

Wave packet spreading is not large

Scattering energy: $\varepsilon = mc^2 \xi$



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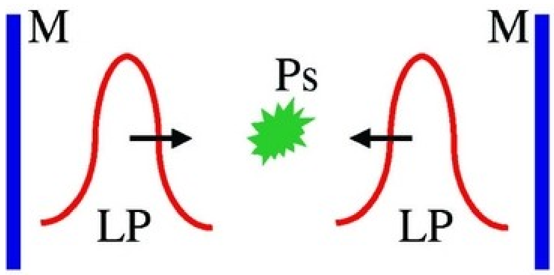

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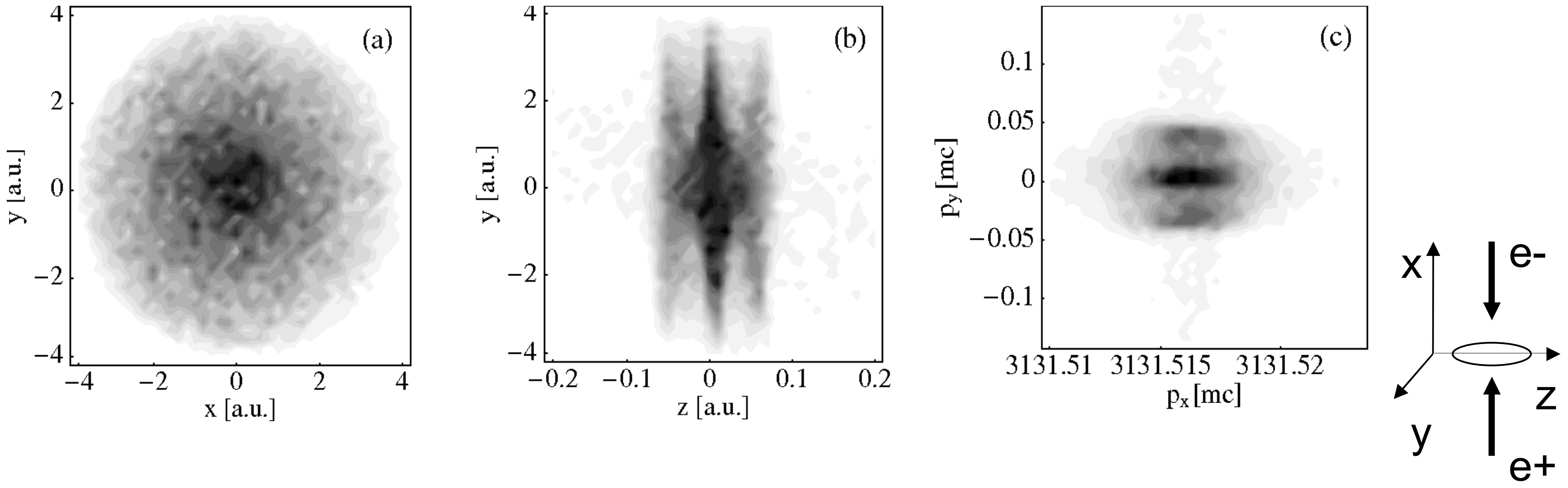

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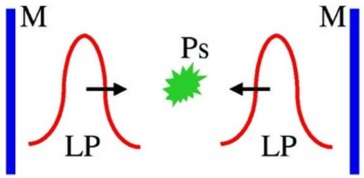

Short recolision time ~ T/2

Wave packet spreading is not large: $a_o < 4a_B$

Scattering energy: $\varepsilon = mc^2 \xi$

Coherent collisions with Ps: $N_{Ps} < (a_b/a_w)^2 \sim 10^{11}$

Reaction events per pulse: 10^{-7} at $N_{Ps} = 10^7$; $n=10^{15}$ cm^{-3}

10^{-4} at $n=10^{18}$ cm^{-3} D. B. Cassidy et al. Nature 449, 195 (2005)

One reaction event per sec at f=1 kHz

Eff. Luminosity: $L_{eff}=10^{24}$-10^{27} cm^{-2}s^{-1}

Incoherent collisions with e+e- plasma:

Reaction events per pulse: 10^{-9} at $n = 10^{15}$ cm^{-3}; $\tau=30$ fs

C. M. Surko et al. PP 11, 2333 (2004)

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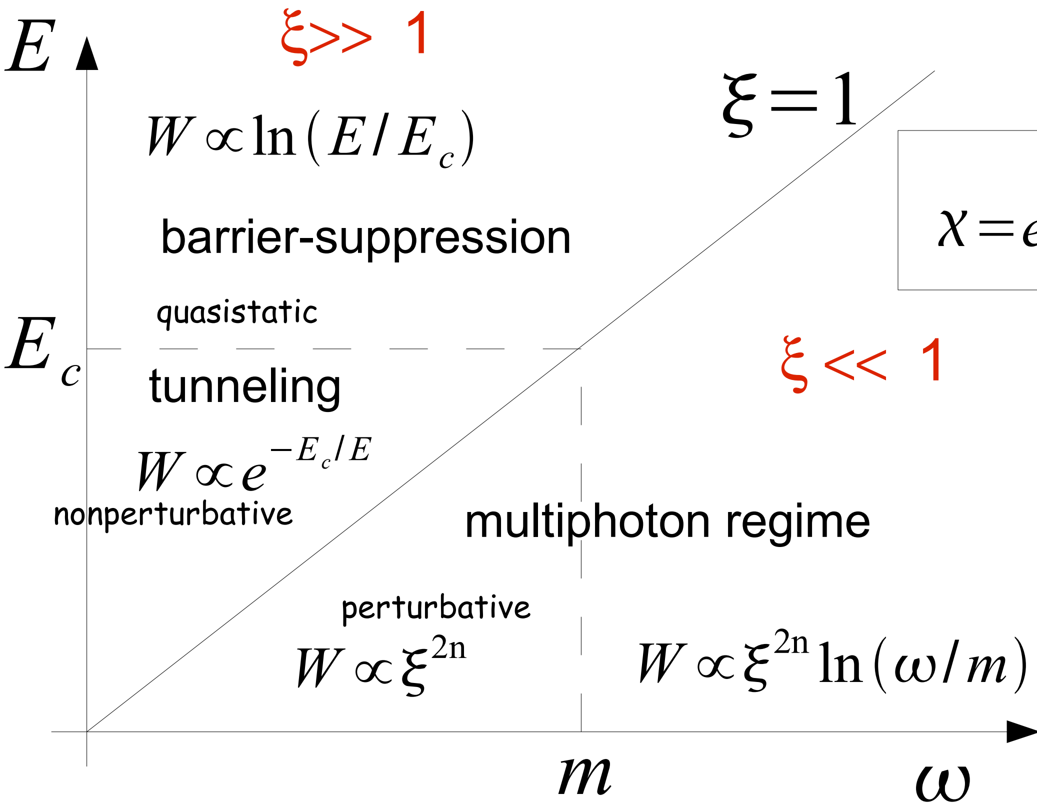
Tunneling and multiphoton pair creation

Keldysh parameter for pair creation:

$$\xi = e\sqrt{A_\mu A^\mu}/m = eE\lambda/2\pi m = eE\lambda_c/\omega$$
$$\xi = 1/\omega\tau\,;\tau = l/c\,; l = m/eE$$

$$\chi = e\sqrt{(F_{\mu\nu}p^\nu)^2}/m = eE\lambda_c/m = E/E_c$$



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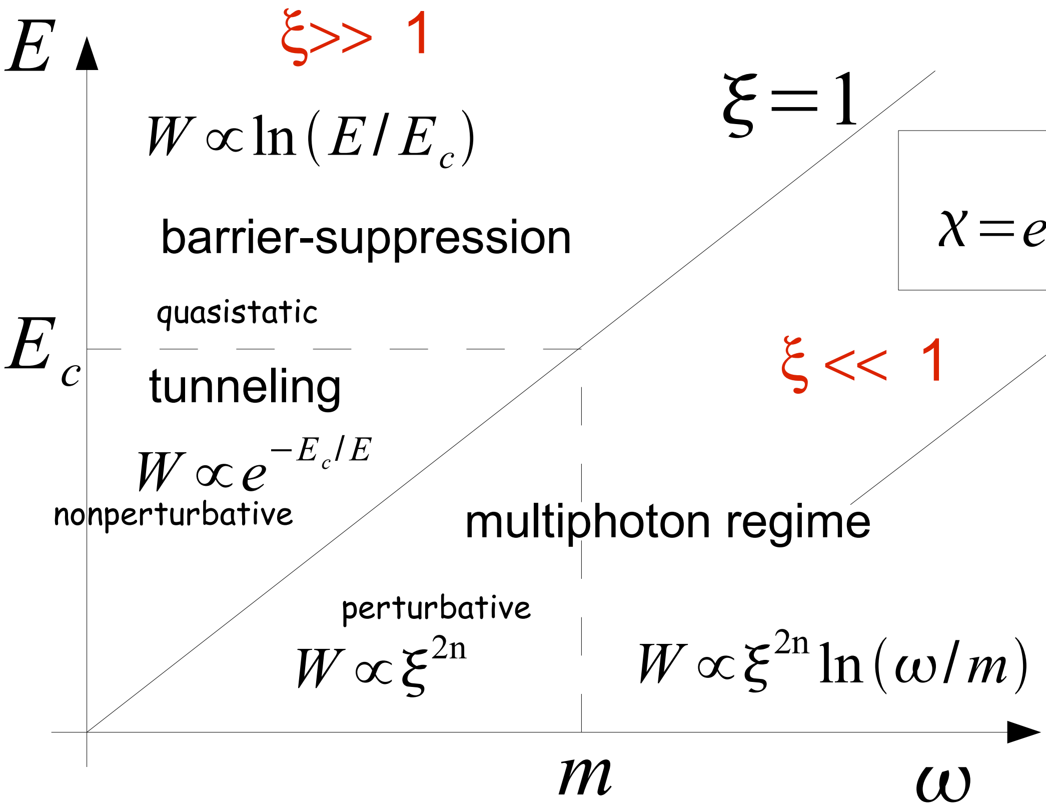

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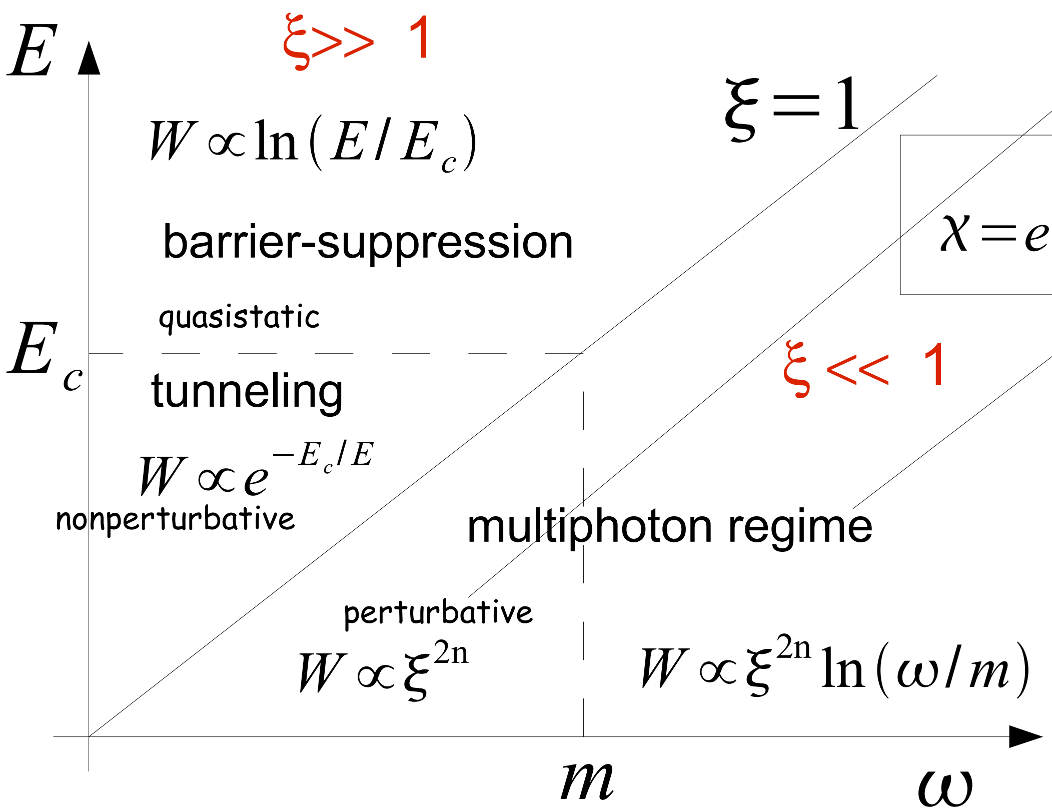

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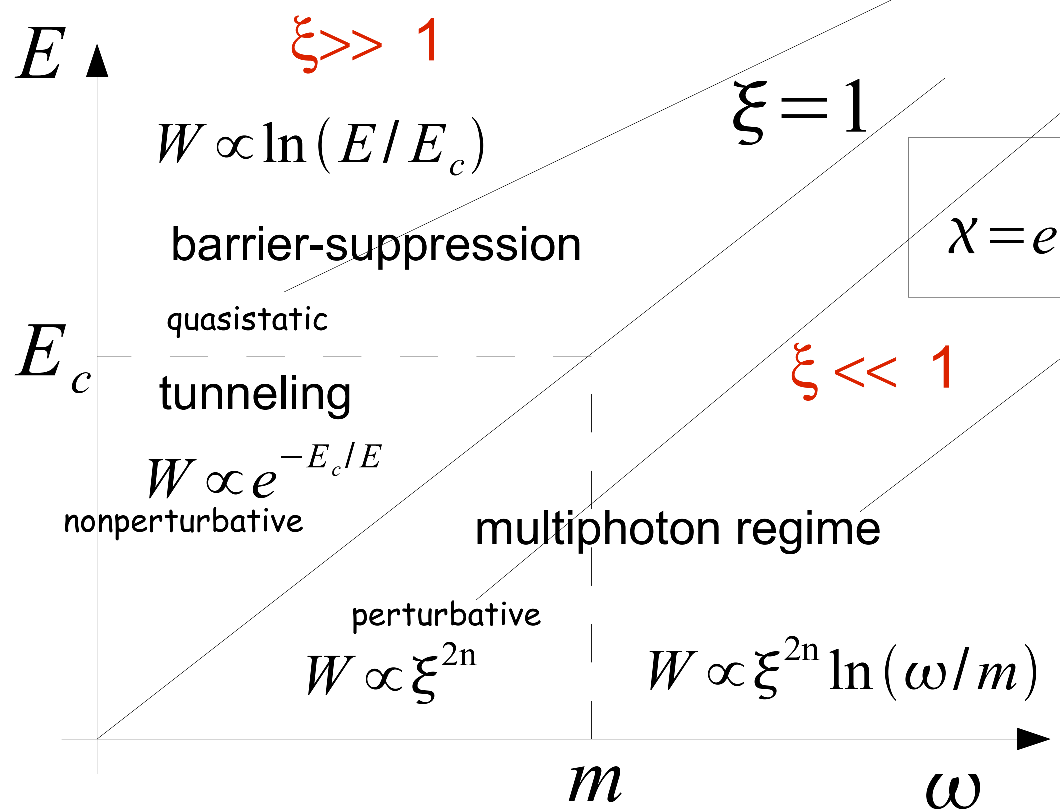

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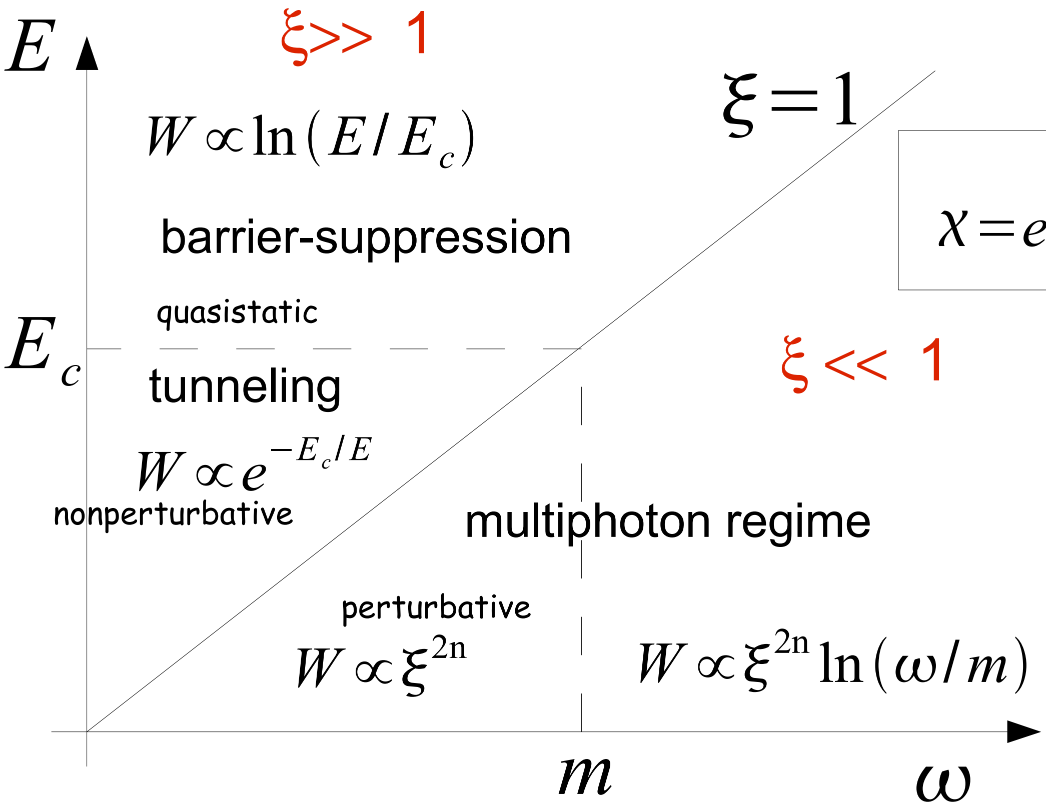
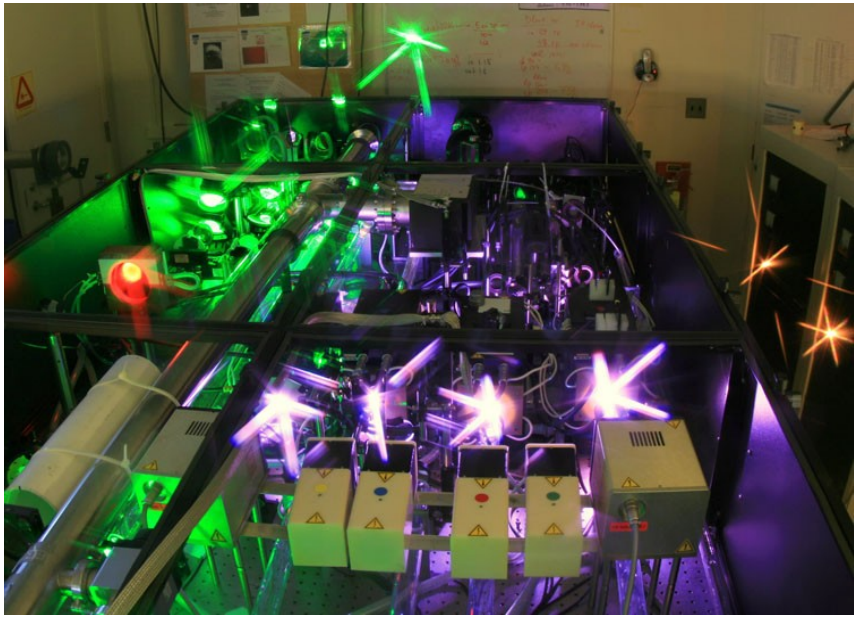


$$\chi = e\sqrt{(F_{\mu\nu}p^\nu)^2}/m = eE\lambda_c/m = E/E_c$$

$\omega \ll m \rightarrow E \sim E_c$

$E \ll E_c \rightarrow \omega \sim m$

Most advanced laser sources



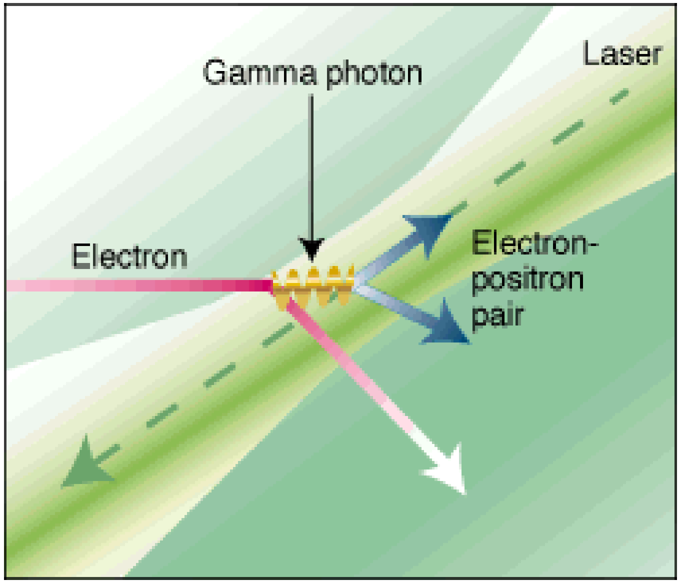
ERCULES Petawatt laser:
$2x10^{22}$ W/cm^2 at 800 nm
$E \sim 10^{-4} E_{cr}$

DESY-FLASH:
100 eV at 10^{17} W/cm^2
(European XFEL up to 12 keV)
$\hbar\omega \sim 10^{-4} mc^2$

Available laser field strengths and frequencies by 4 orders too small...

Relativistic particle beam colliding with laser pulse

SLAC experiment:
46 GeV electron + optical laser pulse
[D. Burke et al., PRL 79, 1626 (1997)]



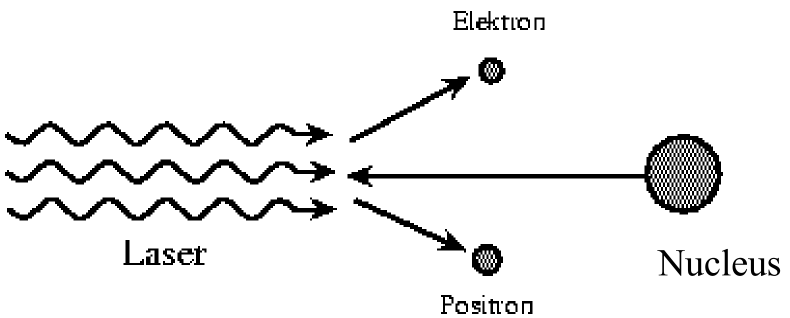
Pairs were produced in two-step process through an intermediate high-energy Compton photon:

$$\Omega_C + n\omega \to e^+e^-$$

Exploit relativistic Doppler shift

Rest frame: $\hbar\omega'$ and E' enhanced by 2γ

Relativistic particle beam colliding with laser pulse



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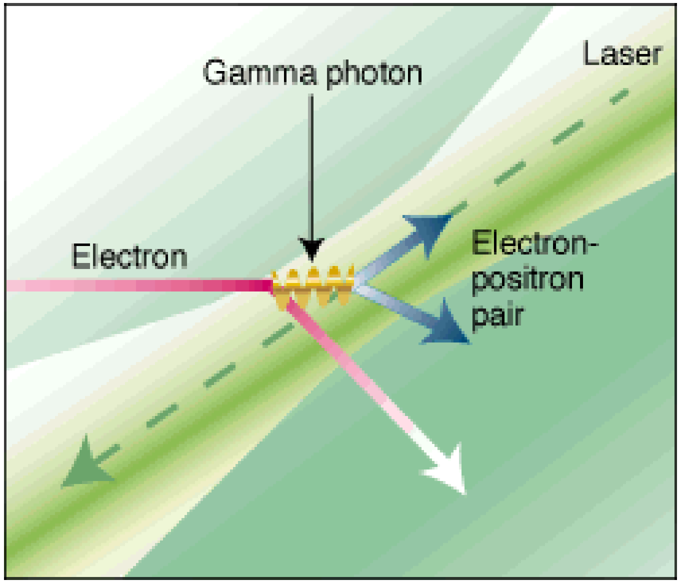


Pairs were produced in two-step process through an intermediate high-energy Compton photon:

$$\Omega_C + n\omega \rightarrow e^+e^-$$

Exploit relativistic Doppler shift

Lab frame: $\hbar\omega \approx 100$ eV , $E \approx 10^{12}$ V/cm

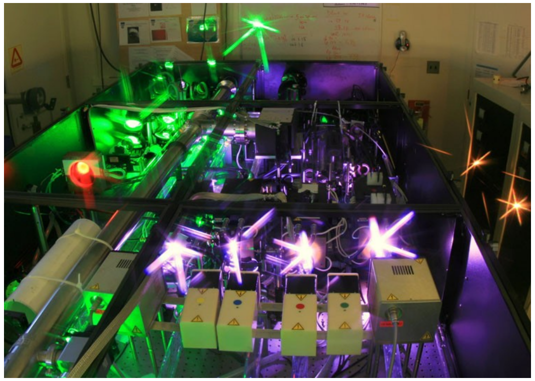
Rest frame: $\hbar\omega'$ and E' enhanced by 2γ

For heavy projectiles such as nuclei Compton channel strongly suppressed and pairs would be produced directly by nuclear Coulomb field:

$$Z + n\omega \rightarrow Z + e^+e^-$$

Merging of laser facility with ion accelerator?

Petawatt laser



uv/x-ray laser

Ion beams of $\gamma \sim$ 3000-7000

Ion beams of $\gamma \sim$ 50

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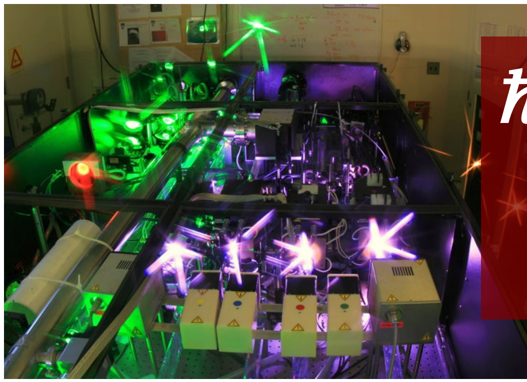
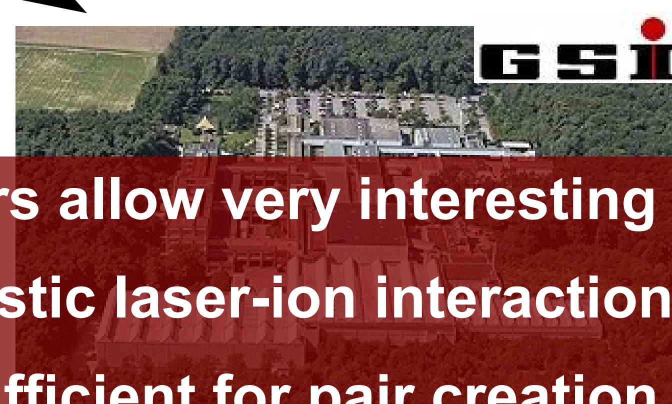
Petawatt laser



uv/x-ray laser

$\hbar\omega' \sim 100$ eV

$E' \sim 10^{-2} E_{cr}$



Such parameters allow very interesting studies on relativistic laser-ion interaction - but not quite sufficient for pair creation

Ion beams of $\gamma \sim 3000$-7000

Ion beams of $\gamma \sim 50$

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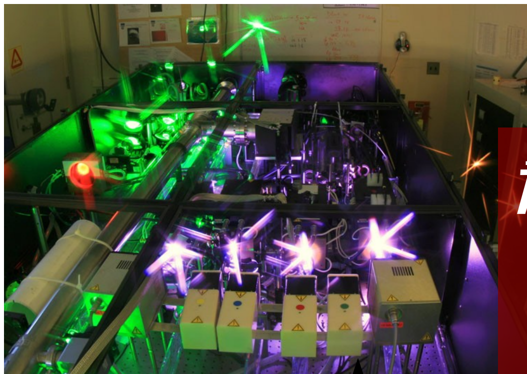
Merging of laser facility with ion accelerator?

Petawatt laser



uv/x-ray laser

$\hbar\omega' \sim 10$ keV

$E' \sim E_{cr}$

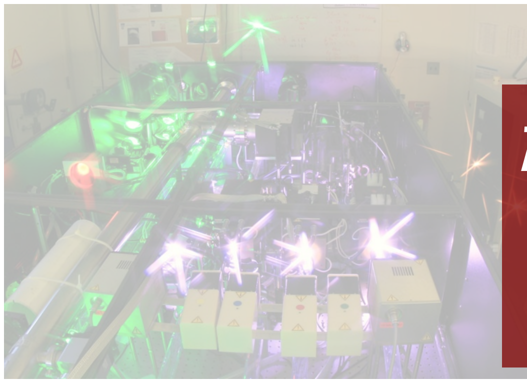
Suitable for pair creation in the tunneling regime!

Ion beams of $\gamma \sim 3000$-7000

Ion beams of $\gamma \sim 50$

Merging of laser facility with ion accelerator?

Petawatt laser



$\hbar\omega' \sim 1$ MeV

$E' \sim 10^{-3} E_{cr}$

uv/x-ray laser

Suitable for pair creation in the multiphoton regime!

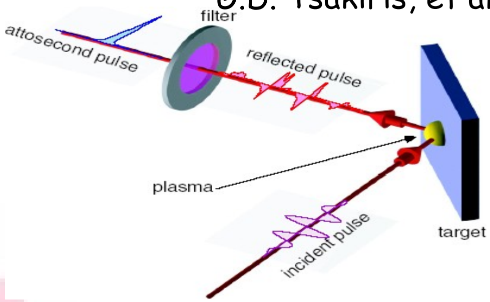
Ion beams of $\gamma \sim 3000$-7000

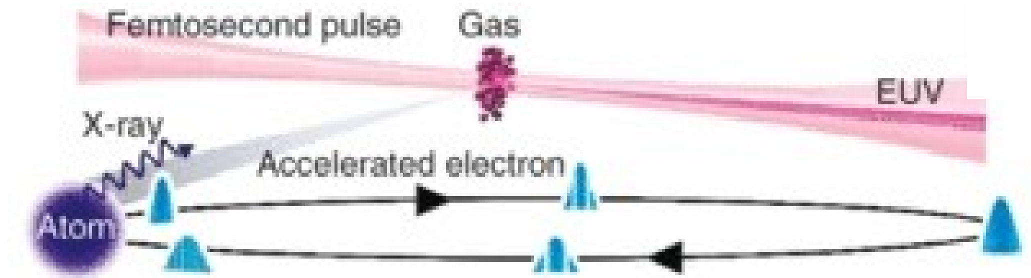
Ion beams of $\gamma \sim 50$

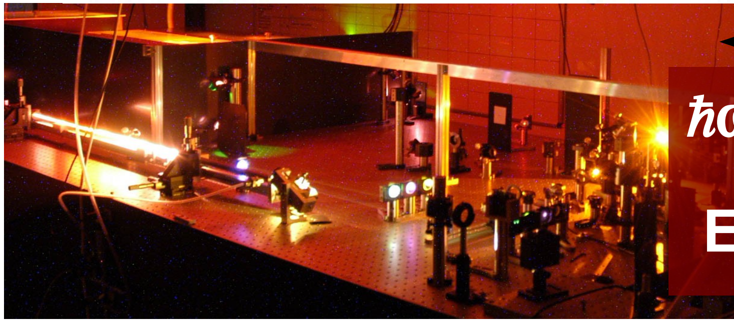
Pair creation by table-top attosecond sources

G.D. Tsakiris, et al., NJP **8**, 19 (2006)

$\hbar\omega$ ~ 100 eV at focused intensities of 10^{14} W/cm^2 (ξ~10^{-4})







$\hbar\omega'$ ~ 1 MeV

E' ~ 10^{-4} E_{cr}

Two-photon pair creation becomes feasible in this setup: About one event per second, when bunches of 10^{11} Pb ions collide with APTs of 30 fs duration at 10 kHz rep rate.

C. Müller, Phys. Lett. B 672, 56 (2009)

MAX-PLANCK-GESELLSCHAFT

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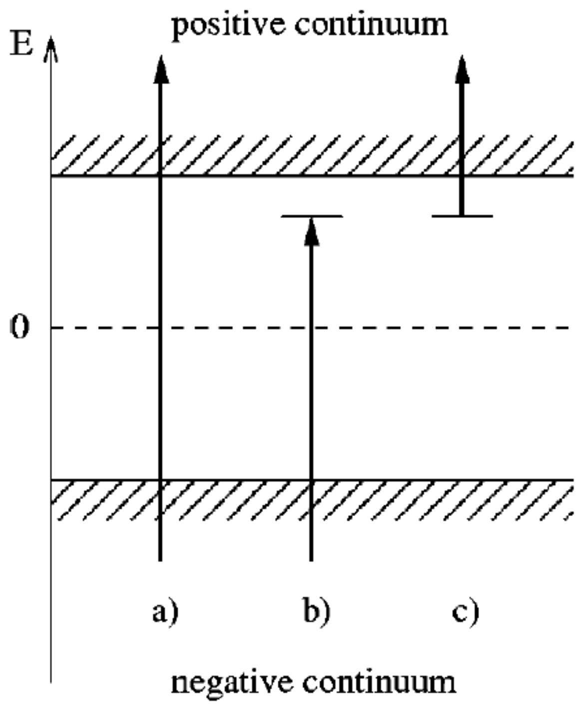
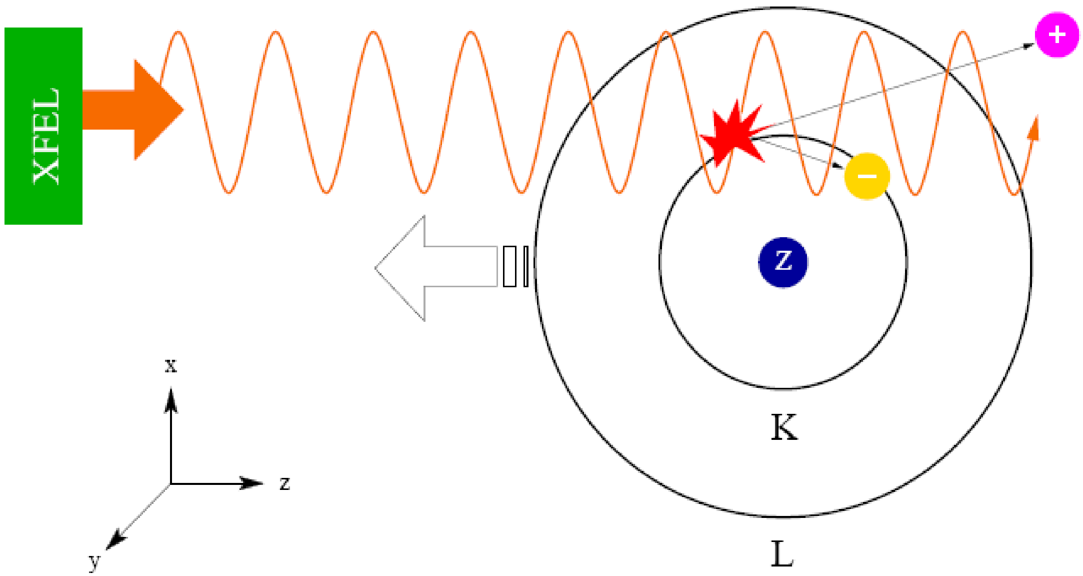
Bound-free pair creation in XFEL-nucleus collision





a) free pair creation

b) bound-free

c) ionization

Table-top XFEL at MPQ: Grüner et al.
Appl. Phys. B 86, 431 (2007)

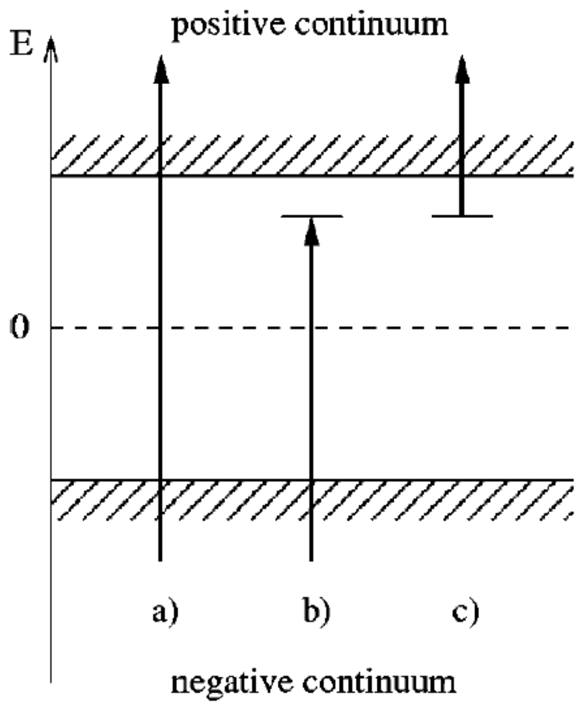
Questions:

Can processes be distinguished solely by e^+ detection?

How does the absolute rate compare with free pair creation?

How large is the contribution of the various atomic shells?

Bound-free pair creation in XFEL-nucleus collision



a) free pair creation

b) bound-free

c) ionization

Strong Field Approximation

$$S_{\mathrm{bf}} = \frac{ie}{\hbar c} \int \overline{\Phi}_{1s} \gamma^{\mu} A_{\mu} \Psi_{q} d^4 x,$$

Coulomb-Dirac wave function of hydrogenlike bound state

Laser vector-potential

Volkov wave function

Questions:

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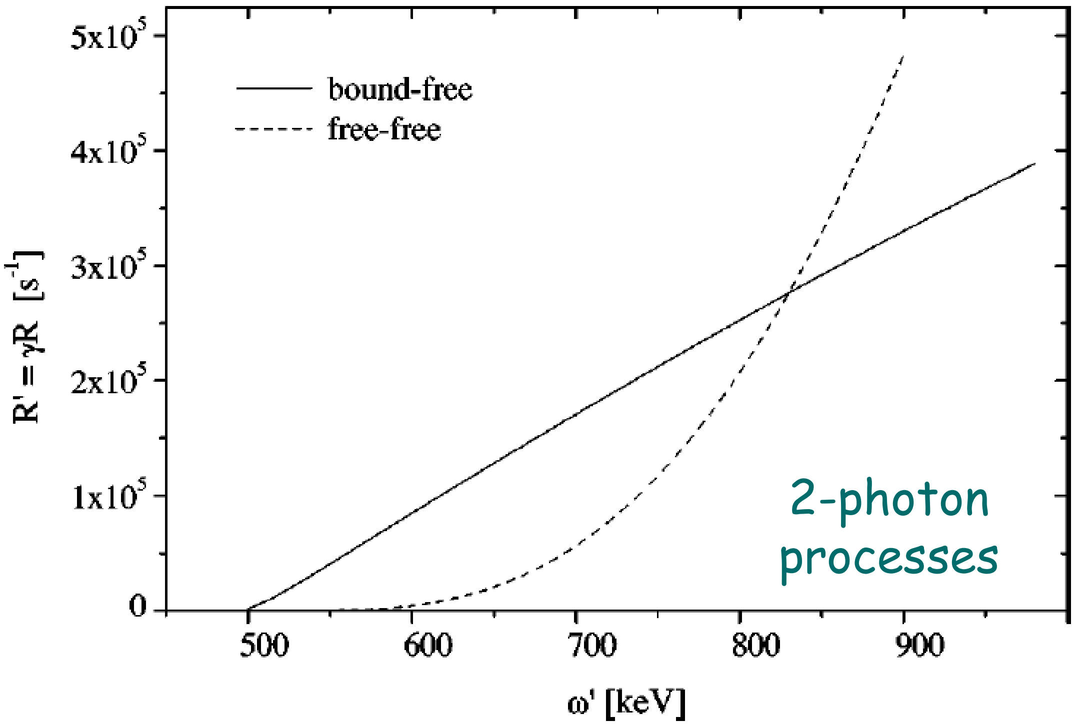
Bound-free vs. free-free pair creation: Total production rates



Parameters:

ω = 9 keV

$I \approx 10^{20}$ W/cm^2

($\xi \approx 0.001$)

Z=50

γ = 50

ω' = 900 keV

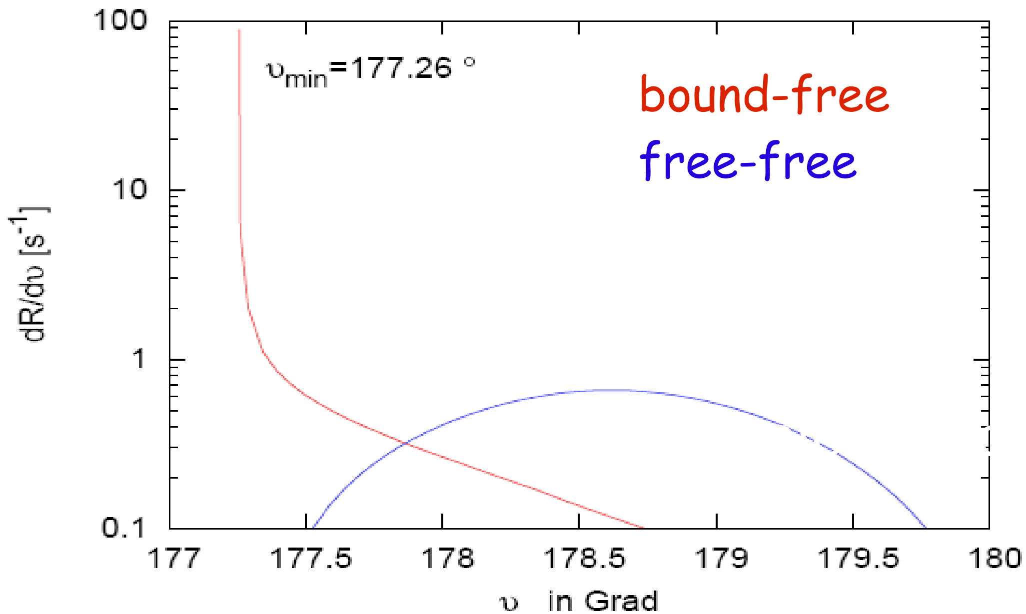
$R_{bf} \sim Z^5 \xi^4 (\omega'-\omega_{min})$

$R_{ff} \sim Z^2 \xi^4 (\omega'-\omega_{min})^3$

Due to different scaling behaviour, the bound-free channel can compete at high Z values.

L-shell contribution ~ 15 %.

Bound-free pair creation: Polar angle dependence in Lab frame



fixed e^+ energy in ion frame translates into (almost) fixed emission angle in lab frame (because ion velocity > e^+ velocity)!

capture to L-shell yields similar angular distributions ($\upsilon_{min} = 177.32°$)

Bound-free process can be distinguished from free-free one by characteristic angular distribution

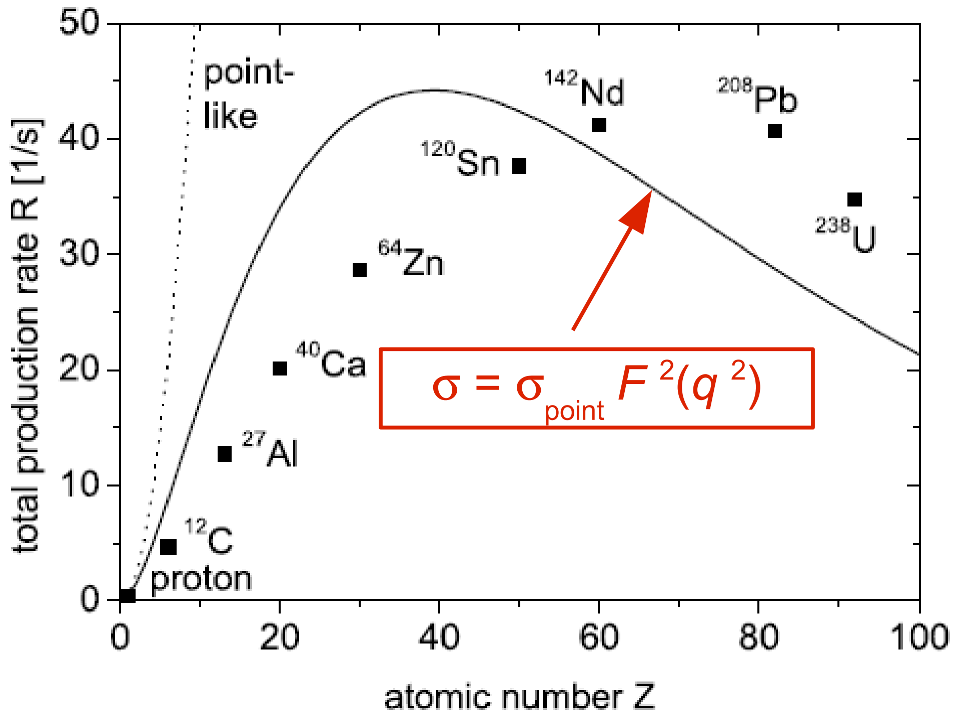
Muon pair creation in XFEL-nucleus collisions

relativistic nucleus
(γ = 7000 at LHC, CERN)

XFEL beam
($\hbar\omega$ = 12 keV)

$\hbar\omega' = 2\gamma\, \hbar\omega$ = 168 MeV

$\Delta = 2Mc^2$ = 211 MeV for $\mu^+\mu^-$ creation
absorption of two x-ray photons



1 $\mu^+\mu^-$/s: XFEL τ=100fs f=40kHz N=10^{11} $\xi=7\times10^{-5}$

For pointlike nuclei: $R \sim Z^2$
HOWEVER:

muons are created at typical distances ~ λ_C =1.86 fm

they only see a small part of the total nuclear charge within R = 0.94 fm $A^{1/3}$ ~ 3-5 fm

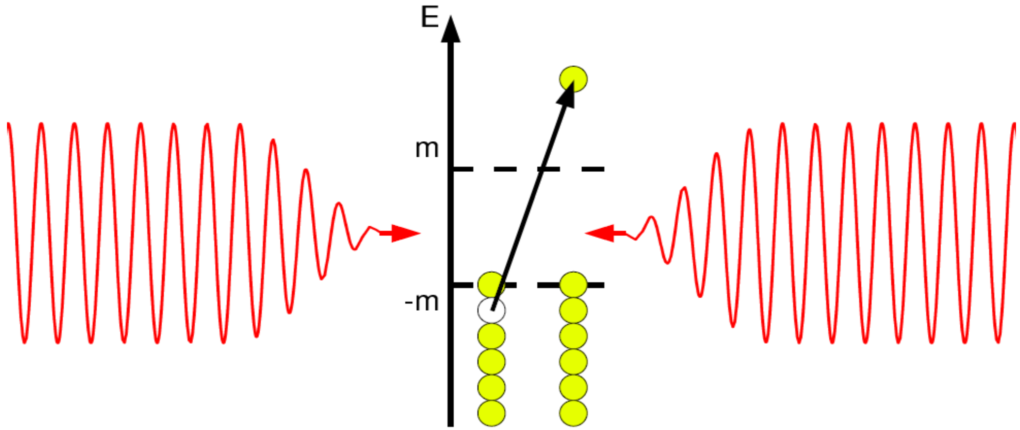
The interplay between the influences of the nuclear charge and size leads to the emergence of maximum elastic production rates for medium heavy ions.

Müller et al. PRL 101, 060402 (2008)

Content

- Laser-driven collider
  - Ps atoms/ Coherent recollisions/high luminosity
  - Muon pair production
- Pair creation in intense laser fields
  - **Pair creation in a laser and Coulomb fields:**
    free pair creation: prospects for experimental realization
    pair creation with capture of the electron: the role of bound atomic states
  - **Pair creation in a standing electromagnetic wave:**
    the role of the laser magnetic field

Pair creation in a field of counterpropagating laser waves



$$A = A_0\,[\,\sin(\omega t - kz) + \sin(\omega t + kz)\,] = 2A_0 \sin(\omega t)\cos(kz)$$

Dipole approximation $\cos(kz) \approx 1$ and $B=0$ is applicable only if

$l_c \ll \lambda \quad \Rightarrow \quad \xi = eE/m\omega \gg 1$

$l_c \sim m/eE$ is the pair formation length

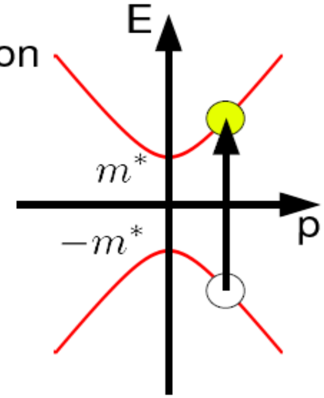
For XFEL/Compton radiation sources $\omega \leq m$ and $\xi \leq 1$, the DA is not valid.

Overview:
Pair creation in an oscillating electric field

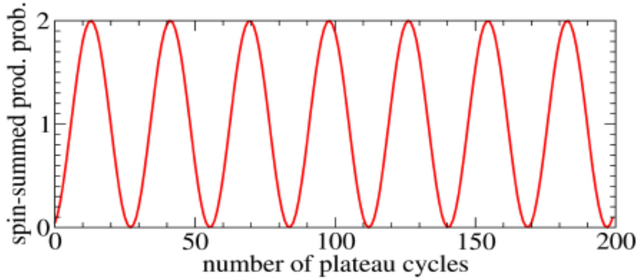
- Pure two level system due to momentum conservation

$$q_0(p) = \frac{1}{T}\int_0^T dt\sqrt{(p - eA(t))^2 + m^2}$$

$$m^* \equiv q_0(p=0) \approx 1.21m \quad \text{for} \quad \xi = 1$$

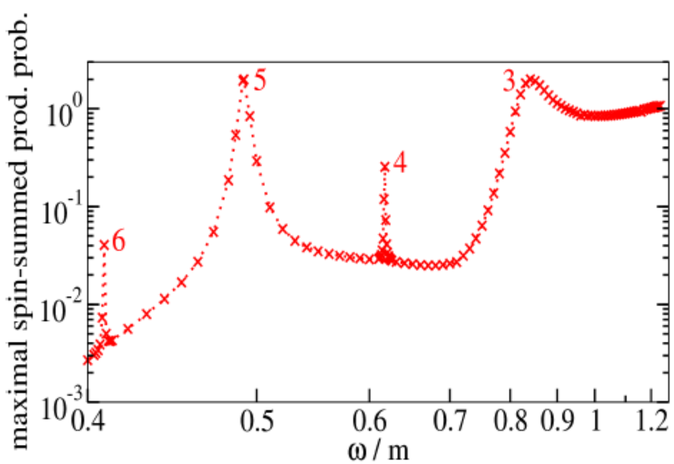


- Rabi-oscillations



- Resonances enforced by energy conservation

$$2q_0(0) = n\omega$$



$w_n \sim \hat{J}_n(U_p)$

$n = m + U_p$

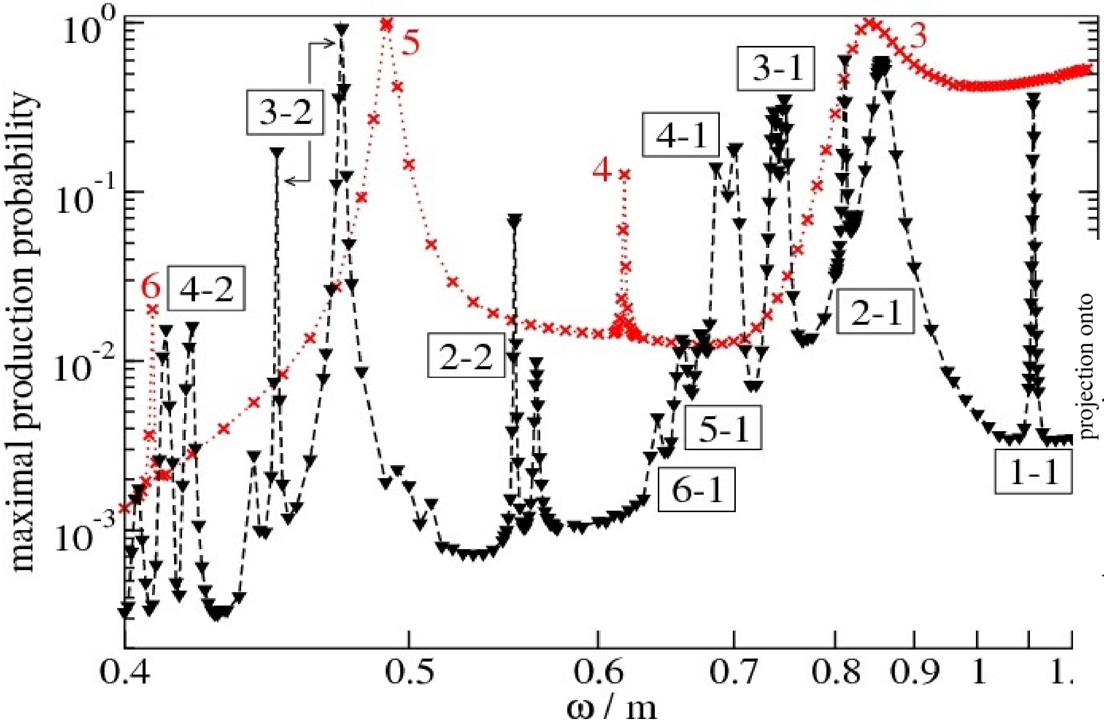
$U_p = a m \xi^2$

$n < U_p$

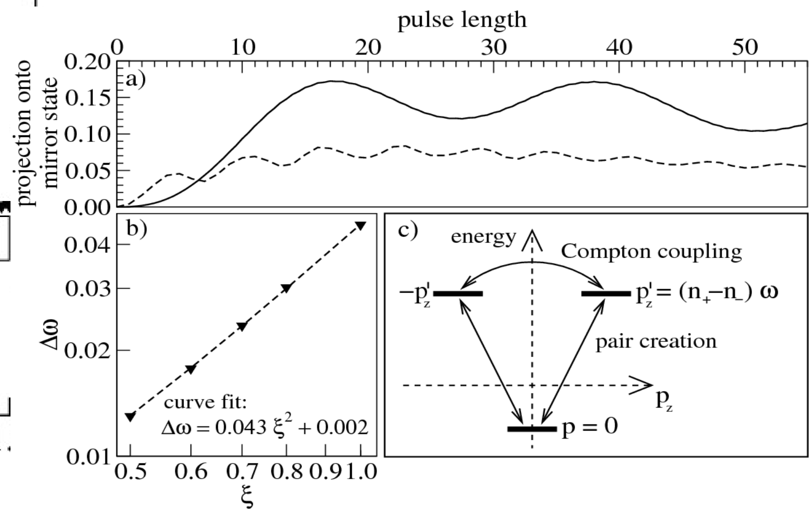
$\xi >> 1, \quad w_n \sim e^{-E_c/E}$

see, e.g. V. S. Popov,
JETP Lett. 18, 255 (1973) etc

The influence of the magnetic-field component



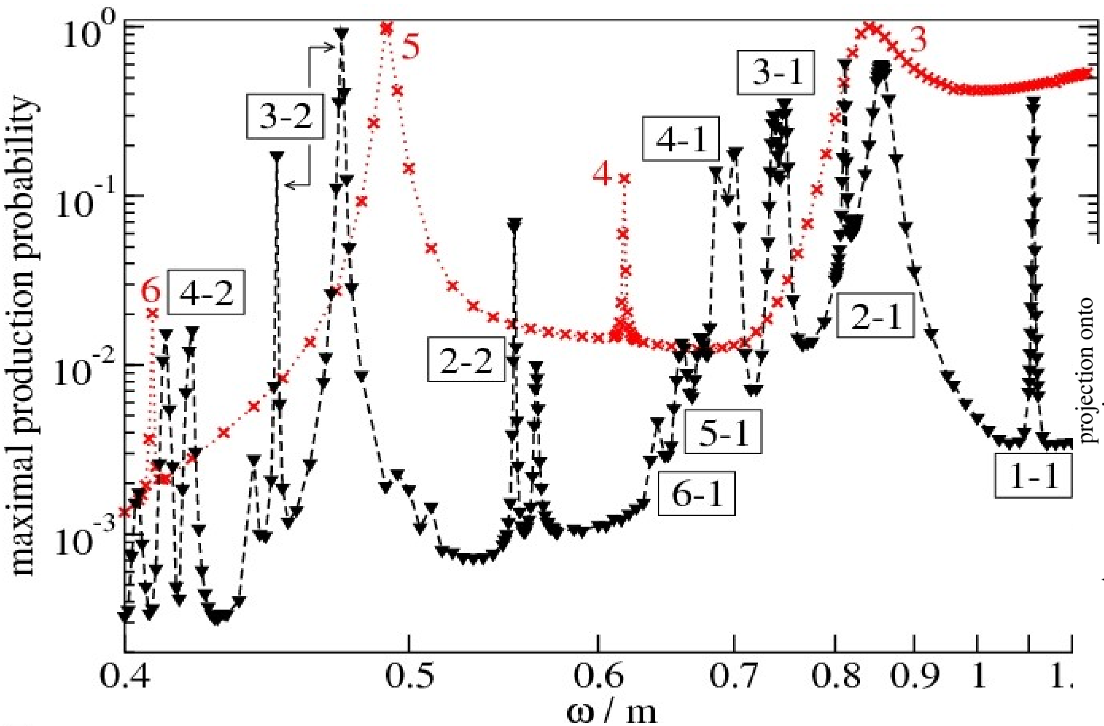
$\omega = m_*(n_+ + n_-)/2n_+n_-$



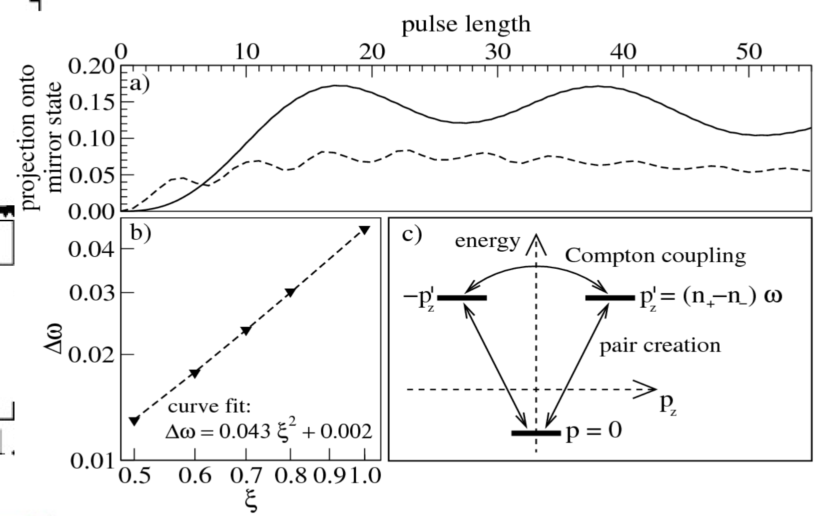
The resonance peaks are shifted and split, due to non-zero photon momentum:
For example, n = 5 = 3 (from left) + 2 (from right) = 4 + 1

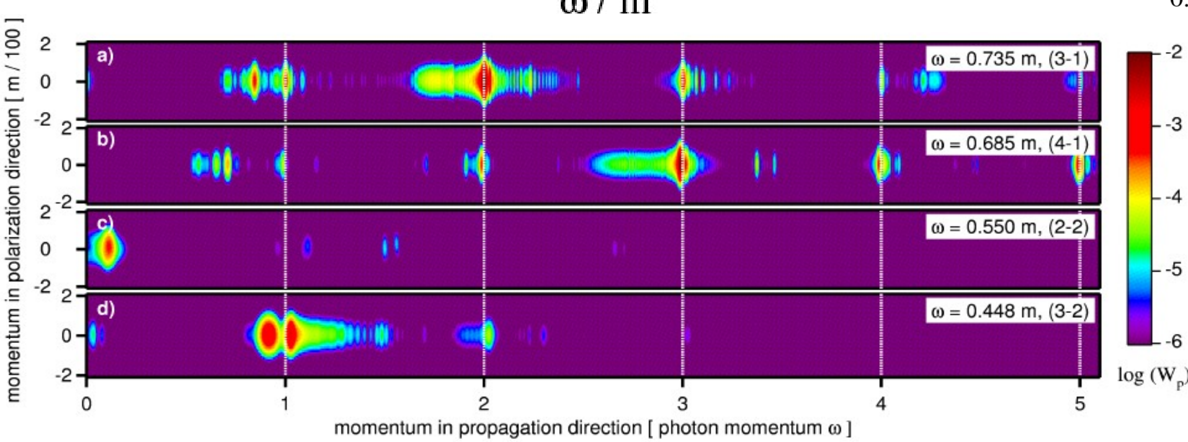
M. Ruf et al. PRL 102, 080402 (2009)

The influence of the magnetic-field component



$\omega = m_{*}(n_{+}+n_{-})/2n_{+}n_{-}$





non-zero photon momentum:

= 4 + 1

Ruf et al. PRL 102, 080402 (2009)

Estimation of particles spectra

$$\Psi(x) \sim \exp\{iS(x)\} = \exp\{iS_0(x)\} \sum_{n=-\infty}^{\infty} \mathfrak{C}_n(\zeta) \exp\{in(\omega t - \mathbf{kr})\}$$

$S(x)$ is classical action. In a laser field: periodicity on $\eta = \omega t - \mathbf{kr}$.

The probability of n-photon process: $W_n \sim |\mathfrak{C}_n(\zeta)|^2 \quad (\zeta \sim \Delta\varepsilon_c/\omega)$

$$\zeta = \frac{m\xi}{\omega} \left| \frac{\mathbf{q}_\perp}{q_0 - q_z} - \frac{\mathbf{q}'_\perp}{q'_0 - q'_z} \right|$$

- **Quasiclassical method** - use the probability $W_n \sim |J_n(\zeta(q,q'))|^2$ and maximizes it with respect to q, q', taking into account the energy-momentum conservation: $n = n(q,q') \Rightarrow \min\{n(q,q') - \zeta(q,q')\}$

Pair production in a laser and Coulomb field

The electron spectrum:

Linear polarization: $q_\perp = 0,\ q_z = U_p$ and $q_0 = m + U_p$.

Circular polarization: $q_\perp = m\xi,\ q_z = 2U_p$ and $q_0 = m + 2U_p$. $U_p = m\xi^2/4$

The spectrum corresponds to $\mathbf{p}(t_0) = 0$ at the creation moment.

$$p_x = \frac{e}{c}[A(\eta_0) - A(\eta)];$$

$$p_z = \frac{e^2}{2mc^3}[A(\eta_0) - A(\eta)]^2;$$

$$\varepsilon = mc^2 + \frac{e^2}{2mc^3}[A(\eta_0) - A(\eta)]^2$$

$$p_x = \frac{eA(\eta_0)}{c};\quad p_z = \frac{e^2A(\eta_0)^2}{2mc^3};\quad \varepsilon - mc^2 = \frac{e^2A(\eta_0)^2}{2mc^2}$$

Pair production in a laser and Coulomb field

The electron spectrum:

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Circular polarization: $q_\perp = m\xi, \; q_z = 2U_p$ and $q_0 = m + 2U_p$. $U_p = m\xi^2/4$

The spectrum corresponds to $\mathbf{p}(t_0) = 0$ at the creation moment.

$$W_n^{max} \sim \left| J_{\frac{2m}{\omega}\left(1+\frac{\alpha\xi^2}{4}\right)}\left(\frac{2m}{\omega}\frac{\alpha\xi^2}{4}\right)\right|^2$$

$W \approx 0$ at the threshold $n_{th} = 2m_*/\omega \quad \left(m_* = \sqrt{1+\alpha\xi^2/2} \right)$

$n = 2q_0/\omega = 2(m + m\xi^2/4) \gg 2m_*/\omega$

When the external field approximation is valid for pair production?

Energy density of produced pairs is less than laser energy density:

$$n_0 \delta\varepsilon \ll \frac{E^2}{8\pi}$$

$\delta\varepsilon$ – energy of produced pairs

n_0 – nuclear density

$$\varepsilon_m \sim m\xi^2$$

$$w \sim (Z\alpha)^2 m \chi^{5/2} e^{\frac{-2\sqrt{3}}{\chi}}$$

$$\chi = E/E_c$$

<u>in tunneling regime</u>

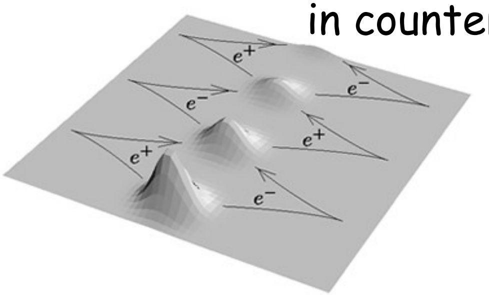
$$\frac{n_{ion}}{n_0}\frac{\tau}{\tau_0}\chi^{5/2} e^{\frac{-2\sqrt{3}}{\chi}} \ll 1$$

$$n_0 = 10^{17}\, cm^{-3}; \quad \tau = 100\, fs$$

One should be careful in using external field approximation at E -> Ec even with short laser pulses.

Conclusion

Laser collider: Coherent collisions and muon production
in counterpropagating laser pulses via Ps gas



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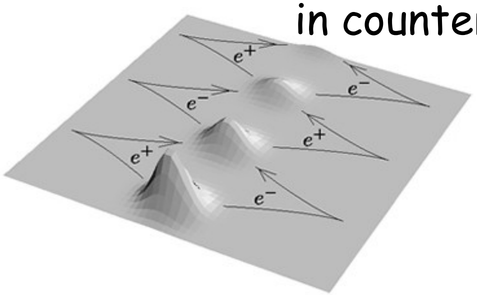
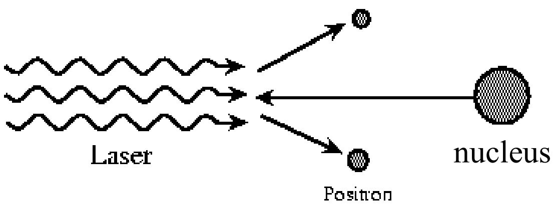


Pair production in collision of laser and ion beams in multiphoton regime.



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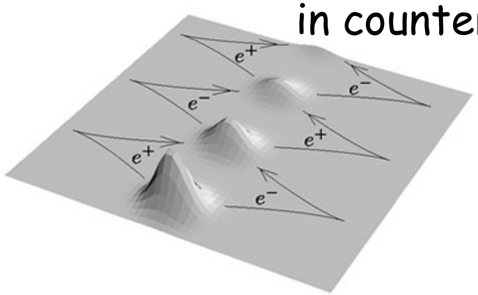
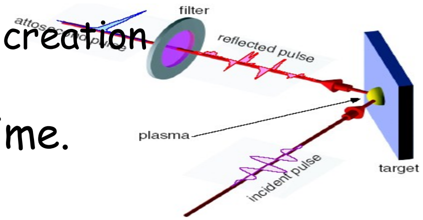


Unusual application of attosecond lasers: with CERN-LHC, they represent most promising tool for experimental realization of multiphoton pair creation



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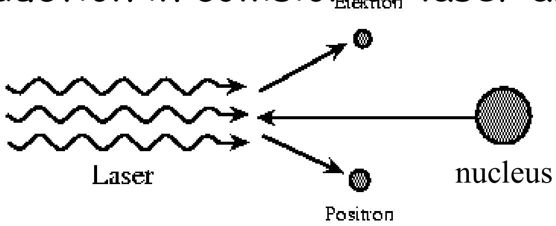

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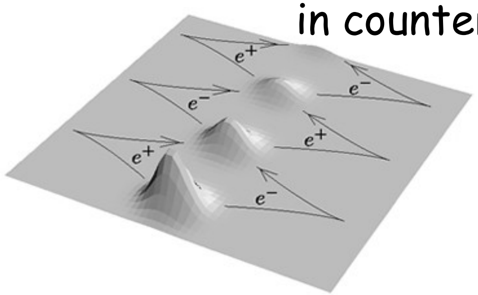

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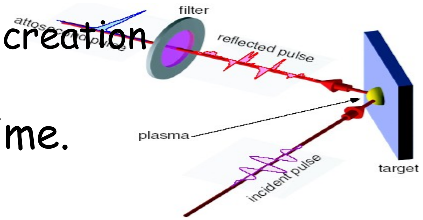

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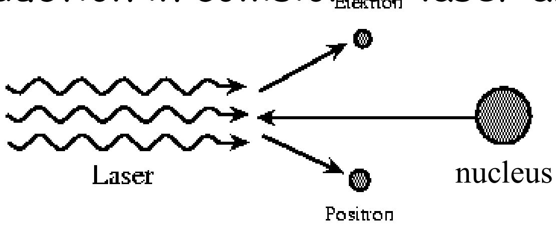
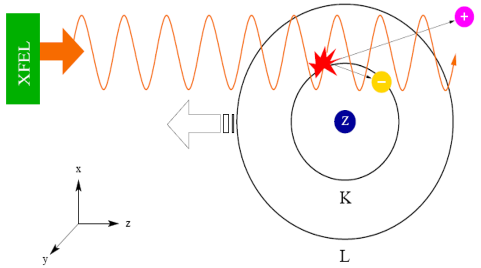


At high Z values, bound-free pair creation can compete with free pair creation in laser-ion collisions



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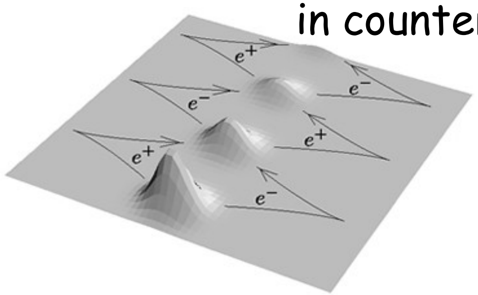

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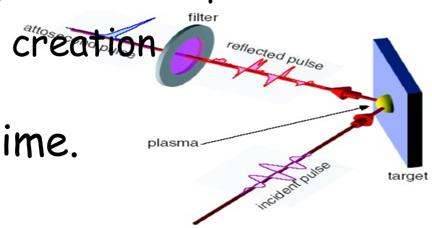

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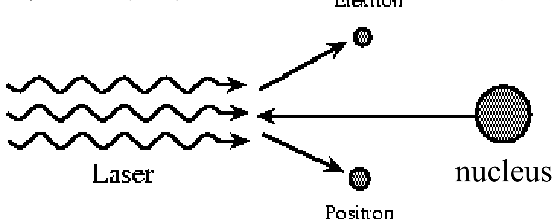

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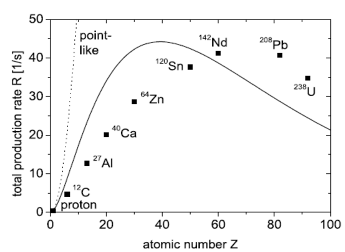
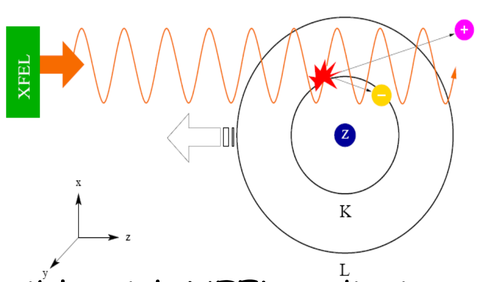
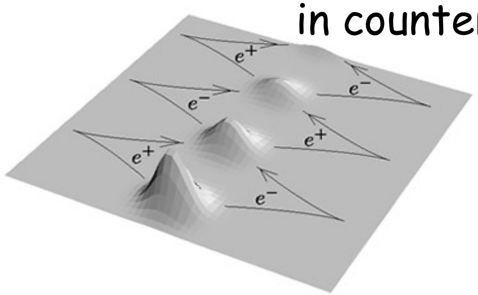




- Muon pair creation feasible with XFEL radiation; process is nuclear form-factor sensitive

Conclusion

Laser collider: Coherent collisions and muon production in counterpropagating laser pulses via Ps gas



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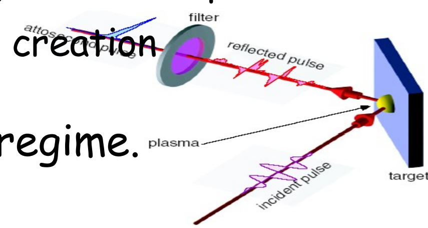

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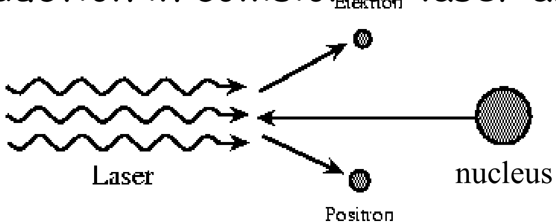

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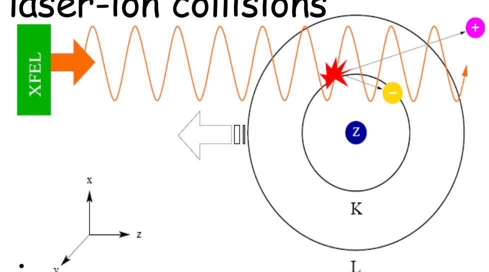
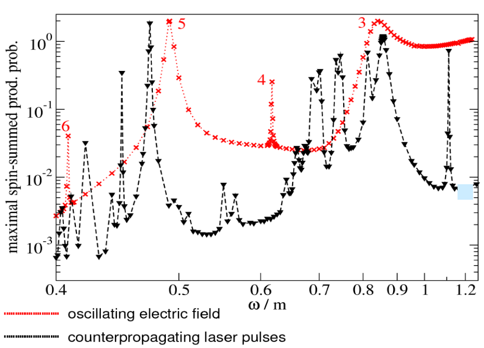
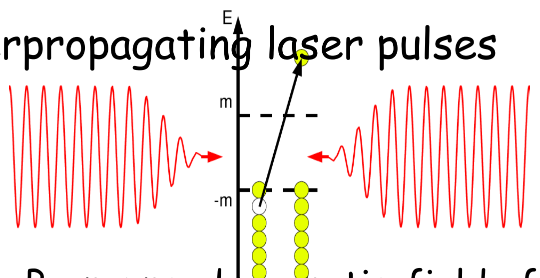


Pair production in counterpropagating laser pulses





Pronounced magnetic-field effects exist in pair creation in a standing wave of high frequency: spliting and shift of resonance lines

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Thank you for attention

Summary

- Unusual application of table-top attosecond lasers:
- In conjunction with CERN-LHC, they represent most promising tool for experimental realization of multiphoton pair creation in laser-ion collisions

produced pair	projectile	γ	$\hbar\omega_0$ [keV]	$\hbar\omega$ [MeV]	photon order	lab-frame rate [s^{-1}]
free e^+e^-	p	7000	0.1	1.4	1	5.79×10^2
	p	3300	0.1	0.66	2	3.76×10^{-6}
	Pb	3300	0.1	0.66	2	2.53×10^{-2}
bound-free e^+e^-	p	7000	0.1	1.4	1	6.09×10^{-3}
	Pb	3300	0.1	0.66	2	4.08×10^{-1}
free $\mu^+\mu^-$	p	7000	12	168	2	8.25×10^{-5}
	p	3300	12	79	3	7.77×10^{-15}
	Pb	3300	12	79	3	6.59×10^{-13}

Radiation losses

In a laser pulse:

$$\delta\varepsilon=\alpha\,\omega_c\,\nu_c$$
$$\omega_c=\omega_L\xi^3\,;\nu_c=\xi$$
$$\nu_c=l_l/l_{coh}\,;l_l=\lambda_L\xi^2;l_{tr}=\lambda_L\xi\,;l_{coh}=R/\gamma=l_l^2/l_{tr}=\lambda_L\xi$$
$$\delta\varepsilon=\alpha\,\omega_L\xi^4$$
$$\delta\varepsilon/\varepsilon_{tr}=(r_0/\lambda_L)\xi^3\approx10^{-3}$$

In equal handed counterpropagating laser waves:

$$\Delta\varepsilon\sim\alpha\omega_c$$
$$\omega_c\sim\gamma^2\omega\,;\quad l_c=\lambda$$
$$\eta=\frac{\Delta\varepsilon}{\varepsilon}\sim\frac{r_0}{\lambda}\xi\sim10^{-7}$$

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Simpleman model

similar to the 3-step model for ATI

Muons are produced at rest in c.m. when E=0:

$$p'_x = e[A(s) - A(s_0)];\ p'_z = (e^2/2\mathrm{M})[A(s) - A(s_0)]^2$$

$$p'_x = -eA(s_0);\ p'_z = (e^2/2\mathrm{M})A(s_0)^2$$

In the Lab frame at the threshold ξ=M/m:

$$p_x = M\ ;\ p_z = M^2/m$$

[can be proven by consideration of saddle points in *S*-matrix integral]

Muons are ultrarelativistic in the Lab frame and move along the laser propagation direction.

Coherent collisions with Ps: N < $(a_b/a_w)^2 \sim 10^{10}$

Reaction rate:

$$\Im \approx \sigma \frac{c}{a_w^3} \tau_r N_{Ps} \upsilon \approx 10^{-9} N_{Ps} \upsilon$$

Luminosity:

$$L\left[cm^{-2} s^{-1}\right] \approx N_{Ps} \frac{c}{a_w^3} \tau_r f \approx 10^{27} f \left[s^{-1}\right]$$

$N_{Ps} \sim 10^8$ ($\rho \sim 10^{15} cm^{-3}$) Cassidy et al. PRL **95**, 195006 (2005)

Incoherent collisions with e+e- plasma:
N > $(a_b/a_w)^2 \sim 10^{10}$ or $\tau > \tau_r \sim 1fs$

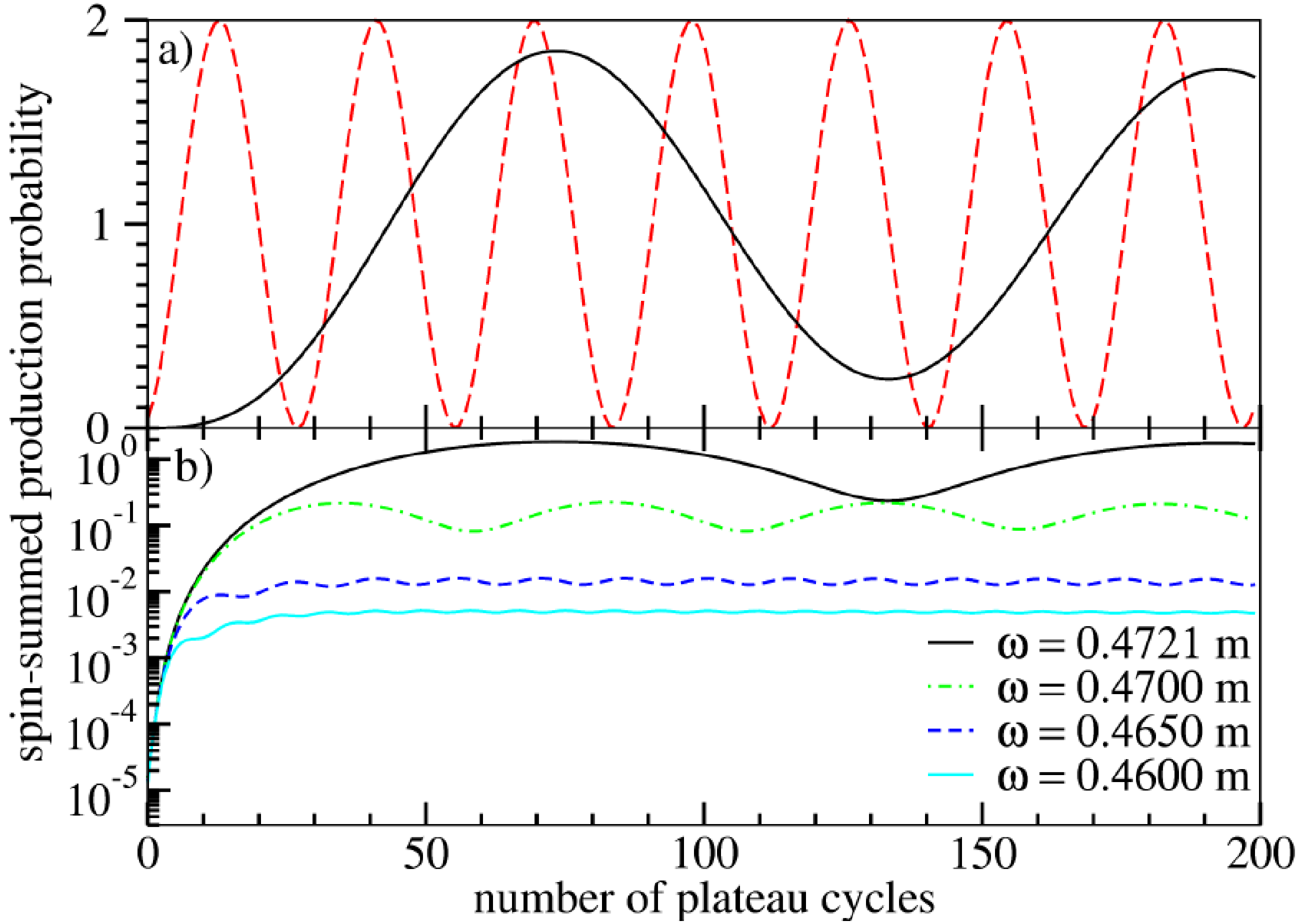
Reaction rate:

$$\Im \approx \frac{\sigma}{\xi^2} \frac{c}{V_{\text{int}}} \tau_{pulse} N_+ N_- \upsilon \approx 10^{-26} N_+ N_- \upsilon$$

Luminosity:

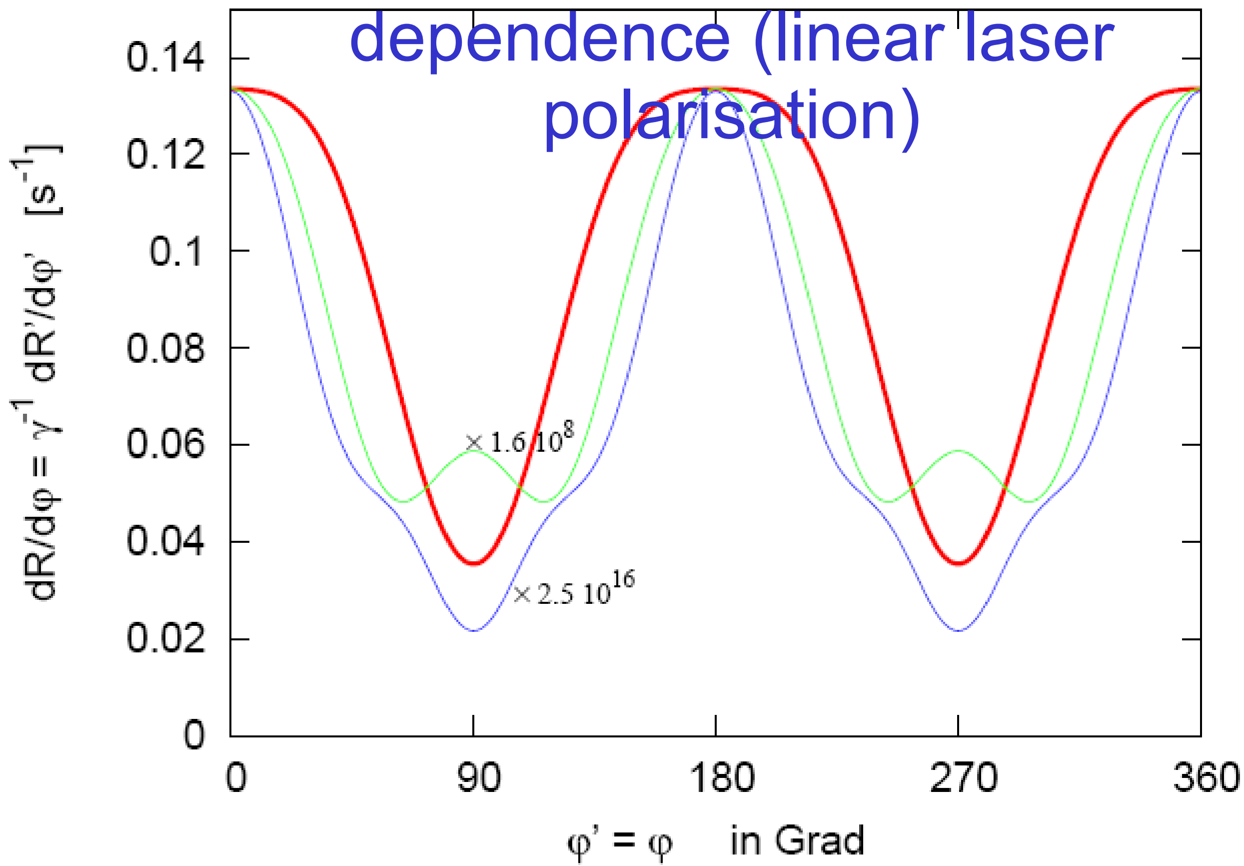
$$L\left[cm^{-2} s^{-1}\right] \approx N_+ N_- \frac{c}{V_{\text{int}}} \tau_p f \approx 10^{22} f \left[s^{-1}\right]$$

Magnetic-field effects:
Modified Rabi oscillations



Bound-free pair creation:

Azimuthal angle dependence (linear laser polarisation)



2 photons
3 photons
4 photons

Bound-free pair creation: Polar angle dependence (ion frame)